Presentation

HUYGENS PROBE DESIGN : SOME LESSONS LEARNT, 27 June – 1 July 2005, Anavyssos, Attica, Greece

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ABSTRACT

The Huygens Probe, developed by ESA with Alcatel Space as Prime contractor, has successfully completed its mission to Titan, the Saturn's largest moon, on January the 14th, 2005.

This paper first reviews the architecture of the Huygens Probe System, from an avionics point of view, and a parallel with the Galileo Entry Probe architecture is made to highlight heritage and differences.

A critical review of the Huygens mission engineering results is then performed and emphasise is put on the functional aspects of the as-run mission reconstructed from the available telemetry. This permits to draw some "lessons learnt" on the adequacy of Huygens-like designs for future entry Probes.

As a conclusion, a formal exercise to "redesign" Huygens avionics with the a posteriori knowledge brought by the mission success is proposed.

ABBREVIATIONS

ACP	Aerosol Collector and Pyrolizer
CASU	Central Accelerometer Unit
CDMU	Command and Data Management Unit
DISR	Descent Imager/Spectral Radiometer
DWE	Doppler Wind Experiment
GCMS	Gas Chromatograph/Mass Spectrometer
HASI	Huygens Atmosphere Structure Instrument
MTU	Mission Timer Unit
PSA	Probe Support Avionics
RASU	Radial Accelerometers Unit
RAU	Radio Altimeter Unit
SPF	Single Point Failure
SSP	Surface Science Package
USO	Ultra Stable Oscillator

1. PROBE ARCHITECTURE

The Huygens Entry Probe has recently offered a spectacular "show" to the international community, and the opportunity of unique in situ measurements of the chemical and physical properties of the atmosphere and surface of Titan to the science community. Huygens has however been the second Probe to successfully complete a mission in the atmosphere of a body belonging to the outer Solar System. It was indeed preceded, in 1995 by the Galileo Entry Probe descent into Jupiter.

The present section details the Huygens Probe architecture from an avionics and functional point of view, after having given an overview of the Galileo Probe avionics main features, outlining the consistency of the two concepts.

1.1 Galileo Probe avionics

In order to eliminate single-point mission failures the Galileo Probe electrical subsystems were made hot and active redundant designs. It permitted to provide two parallel and simultaneous data streams from the instruments to the Galileo Orbiter. The overall scheme is illustrated in Fig.1.

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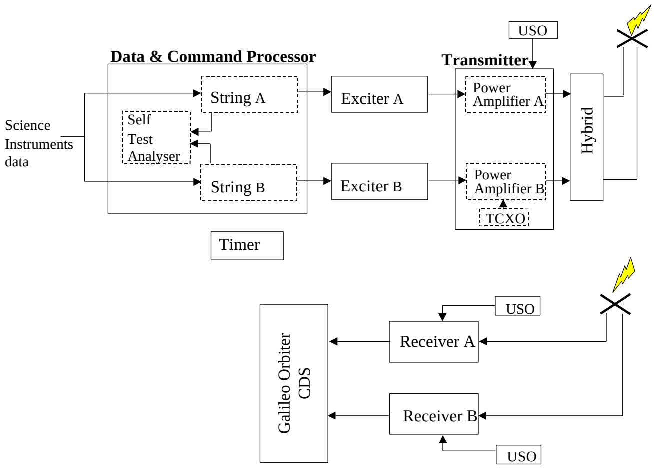

Fig. 1. Galileo Probe overall architecture

Galileo Power subsystem

It consisted in two electronics units, a Lithium/sulfur-dioxide ($LiSO_2$) and a set of thermal batteries.

The System Power Interface Unit (SPIU) provided power distribution and redundant switching of non regulated voltage to the Probe subsystems and to the Instruments Power Interface Unit (IPIU). The IPIU in turn provided redundant switching of voltage regulated lines to the instruments. Prior to separation, the energy was provided by the Orbiter.

The main $LiSO_2$ battery was made of three modules of 13 cells able to deliver about 730Wh in total, among which about 630Wh available for the actual mission.

The energy for the pyrotechnic events was taken from two dedicated thermal batteries to avoid perturbation in the main bus. These thermal batteries were activated from a tap on the main battery at the eighth cell.

Galileo Command and Data Handling Subsystem

It consisted in the Data and Command Processor (DCP), the pyro-controlled unit (PCU) and four acceleration g-switches.

The DCP was composed of two identical strings each controlled by a 8-bits micro-controller. During pre-entry the command and data functions were divided in between the two strings which were therefore not redundant.
From separation from the Galileo Orbiter until the programmed wake up of the Probe some 150 days later, six hours before entry, only the Coast timer operated, powered from the battery module 3. This consumed about 200Wh.

After the Probe wake up, one single string was used to collect and store some instruments data.

Twenty minutes before entry in the atmosphere, a self-test function of the two strings was automatically performed in order to possibly turn off the string which fault would have affected the other string. In case of no-fault, both strings operated through the end of the mission, performing the same command and data function in parallel. With the exception of the magnitude of the time for the coast phase, the entire sequence, from separation to end of mission was contained in permanent memory.

Entry and descent functions were tied directly to the atmosphere by the g-switches after application of an algorithm by the DCP, which removed uncertainties in the deployment conditions due to entry angle and atmosphere characteristics uncertainties. The g-switches also provided backup initiation of the descent sequence in the event of either early or late time-out of the coast timer.

The PCU provided the pulses to activate the redundant pyro initiators, as well as the arming function.

Galileo Communication and Radio Relay Subsystems

It was composed, on the Probe side, of two L-band channels, each channel consisting in a RF exciter and a power amplifier. 23W of RF power were put out allowing 128 bits per second per string to be transmitted. One of the channels frequency was driven by an ultrastable oscillator to be used for a Doppler wind measurement; the other one was driven by a standard TCXO. Both channels were transmitted through a single passive hybrid and a single dual feed cross dipole antenna.

On the Galileo Orbiter side, it included two radio receivers, each performing the acquisition and tracking process of one of the Probe signals the formatting of the received data and interfacing with Galileo spacecraft command and data system for storage of this data, two ultrastable oscillators, to extract the wind component of the Orbiter-Probe doppler, and one 1.1m parabolic reflector with a dual feed for receiving the two signals. The receiving antenna was mounted on a deployable mechanism for pointing during the Probe mission.

1.2 Huygens Probe avionics

The design of the Huygens Probe started about 2.5years after the launch of Galileo spacecraft. Cassini/huygens spacecraft was launched in October 97, some two years after completion of the Galileo Probe mission. Huygens could therefore on the one hand build up on the Galileo Probe design heritage, and on the other hand benefit from lessons learnt after Galileo Probe successful mission.

The overall Huygens architecture was very similar to Galileo Probe's one : two hot redundant, active chains A and B acquired data from five instruments and transmitted then via two parallel ways to the Cassini Orbiter. However, as it will be detailed in the following, the design was further enhanced towards even more robustness. The scheme is illustrated in Fig.2.

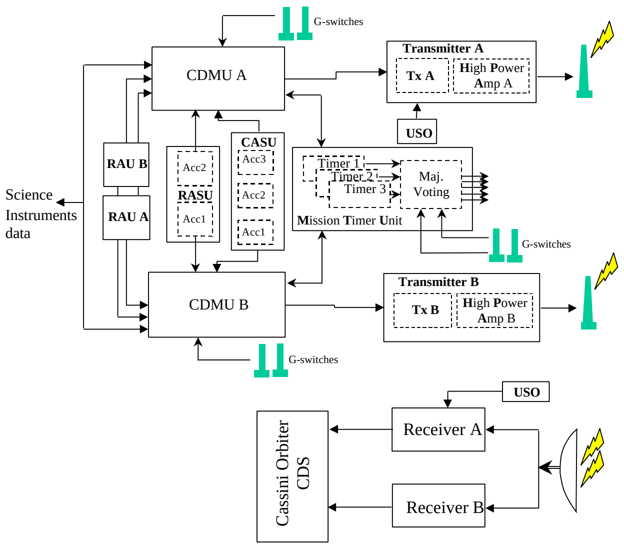

Fig. 2. Huygens Probe overall architecture

Huygens Electrical Power Subsystem

It comprised two electronic units, the Power Conditioning and Distribution Unit (PCDU) and the Pyro Unit, and a Lithium/sulfur-dioxide ($LiSO_2$) battery system.

The PCDU provided conditioning of the Orbiter power before separation, and of the battery power after separation into a 28V regulated Bus. It also provided distribution of this power bus to all the units via redundant switching and over current protection.

The $LiSO_2$ battery system was the sole energy source after separation from Cassini. It was made of 5 primary Batteries, each consisting in two "Galileo Probe identical" 13 cells modules connected in series, able to deliver up to 2300Wh, among which about 1900Wh were available for the actual mission.

The Pyro Unit provided arming and firing functions to activate the redundant pyro initiators. The energy for the pyrotechnic events was taken directly from a tap at the thirteen's cell of the batteries 1 and 5 for redundancy.

Huygens Command and Data Management Subsystem

This subsystem was to some extend more complex than the Galileo Probe's one, essentially because of specific mission requirements : Titan has a surface and several instruments had a surface mode, and Huygens embarked a camera. It consisted in two Command and Data Management Units (CDMU), a separate Mission Timer Unit, a Central Acceleration Sensor Unit (CASU), a Radial Acceleration Sensor Unit (RASU), two Radio Altimeters Units (RAU's), a set of six (two plus four) acceleration g-switches.

The two CDMU's were identical processing units fully physically separated, and operating in hot redundancy from Huygens wake up until the end of mission. They were both controlled by a 16-bits processor and performed identical command and data functions, including acquisition from the acceleration and altitude sensors. Contrarily to Galileo Probe, the two chains A and B remained redundant all along the mission. In addition, the system design was made such that no failure of one chain would impact the other chain. This allowed a major simplification and therefore increase of robustness in the sense that Huygens had one single mode of operation entered after initialisation, the mission mode, whatever the phase of the mission; no fault recovery mode was implemented.

In order to make possible some adaptation to mission changes, or help to resolve anomalies discovered after launch, software patching capability was implemented in each CDMU, allowing to change up to 40% of the overall code and data.

From separation from Cassini until the programmed wake up of Huygens, about 22 days later, 4h28mn before entry, only the Mission Timer Unit operated. The MTU was in fact composed of three identical programmable timers, a majority voting circuit, and the electronics to connect the battery relays to the PCDU at the end of the coast phase. It was powered directly from the batteries 2, 3 & 4 (one battery per timer) and consumed about 160Wh. The design was fully single failure tolerant, however a back-up in case of late time-out of the MTU was also implemented by the mean of two dedicated acceleration g-switches able to trigger the probe wake up at start of the entry phase.

Entry and descent functions were tied directly to the atmosphere by the detection of a patchable g-threshold measured from the three single failure tolerant CASU accelerometers. This removed uncertainties in the descent parachutes deployment conditions. The design of the Huygens nominal entry detection function compared to Galileo Probe, had the great advantage to be easily and unambiguously testable on ground, with acceleration parameters remaining measurable during the cruise phase. However, after Galileo Probe entry detection anomaly (inversion of the g-switches high and low threshold), it was felt necessary to reinforce the robustness of the function on Huygens by implementing a full and “workable” back-up based, as for the wake-up function back up, on a totally separated set of hardware. This was achieved via the design of an entry detection mechanism based on the detection of thresholds from a set of four g-switches (two per chain). To some extend, Huygens back-up could be compared to the nominal Galileo Probe mechanism. It is also worth underlining that the back up was designed not to interfere with the nominal mechanism.

In order to provide the DISR instrument with estimate of the spin during the descent, two accelerometers (one per chain), aligned with the Probe radius were implemented within the RASU. An algorithm extracted in real time the spin data from the raw radial acceleration.

The measurement of the Probe altitude above Titan surface was implemented via the two RAU FMCW radio altimeters. These two units provided altitude data from higher than 10km to each of the two CDMU A and B. The two altitude measures were compared to a tabulated theoretical descent profile, and once declared “valid”, were used for a real time update of the profile.

Huygens Data Relay Subsystem

It comprised on the Probe side, two S-band channels associated with the two CDMU’s, each consisting in a dedicated transmitter unit with a 10W RF Solid State Power Amplifier allowing to transmit 8192 bits per second. As on Galileo, one of the channels frequency was driven by an ultrastable oscillator to be used for a Doppler wind measurement; the other one was driven by a standard TCXO. Each channel was linked, without cross coupling to a dedicated quadrifilar helix antenna.

On Cassini side two digital receivers A and B (PSA A and PSA B) were implemented to acquire and track the two Probe signals, format the received data and interface with Cassini Command and Data System (CDS) which then stored all the Huygens data into several partitions. The two receivers were driven by a standard TCXO clock, but an ultrastable oscillator could also be selected by a simple relay to allow the extraction of the doppler wind component. The two RF signals were received by two feeds of the Cassini 4m High Gain Antenna, kept pointed toward the expected Probe landing site by the mean of a specific Cassini Attitude and Articulation Control Subsystem mode.

1.3 Consideration on the design of Galileo and Huygens Probes

As it can be seen from Fig.1 and Fig.2, the two designs are essentially similar, with a high priority given to the robustness of the mission to the detriment of efficiency in terms of mass, power and even amount of data returned. Significant system work was done on Huygens in order to reinforce the original concept of two identical, fully independent, hot redundant strings from the instruments interface up to Cassini CDS interface and eliminate the potential single failure points. This allowed to reduce the number of Probe System modes to one, the Mission Mode.

Another improvement in Huygens design was related to the implementation of the critical functions. Both the Probe wake-up and the Probe Entry detection are indeed implemented via both :

- a nominal, single failure tolerant mechanism
- a workable back-up mechanism based on a different set of hardware,

this approach permitting to cover both the single component-type failures, and the technological type failures affecting all components/units from the same type/lot.

2. HUYGENS MISSION RESULTS

After having given an overview of the Probe avionics and functional architecture, the present chapter describes the step by step operations from the pre-separation activities on the 21st of December 2004 until the end of the mission on the 14th of January 2005, as well as the main events. As far as the mission data is concerned, the timeline is presented as analysed from the received telemetry after read back of the Cassini Solid State Mass Memory.

Pre separation activities

21/12/04	07:00:00 UTC	The MTU timers are loaded to wake-up to the Probe after 23 days 21h 42mn 22s, ie the 14th of January at 04:42:22UTC
25/12/04	02:00:00 UTC	Probe is separated from Cassini with - V_{axial} = 0.33m/s - Spin = 7.5rpm - Entry Angle = 65.1°

Pre Entry Activities

14/01/05	04:41:18 UTC	Probe is waken up by the MTU
14/01/05	04:41:34 UTC	Ultra Stable Oscillator instrument, channels A and B Probe transmitters are turned ON
14/01/05	04:41:48 UTC	GCMS instrument is turned ON
14/01/05	04:59:18 UTC	HASI instrument is turned ON
14/01/05	06:50:31 UTC	PSA A is turned ON on board Cassini to be ready for chain A data reception
14/01/05	06:50:33 UTC	PSA B is turned ON on board Cassini to be ready for chain B data reception
14/01/05	07:13:44 UTC	Cassini turn to point HGA to Titan is complete

The Probe has been turned ON by the Mission Timer Unit within 1mn of the programmed time, consistently with the timers accuracy.

At this point, both ends of the Probe System should have been ready for the mission : entering into Titan atmosphere for the Probe, and acquiring the two RF uplinks for the receivers on board Cassini. However, due to an error in the commanding sequence running on Cassini, the ultrastable oscillator driving the channel A receiver for Doppler extraction was not turned ON; this made the lock on the chain A, and thus any data acquisition, impossible. It also made the real time extraction of the wind component of the Doppler impossible (note that, thanks to the acquisition and tracking of the chain A uplink by powerful ground based radio-telescopes, this important data could finally be reconstructed) . In the following the analysis has been essentially based on the telemetry transmitted by the chain B. Still, because some parameters were cross strapped, a very good assessment of the Probe performance could be done.

Entry Activities

14/01/05	09:05:54 UTC	Probe reaches the atmosphere - altitude above Titan = 1235km - Velocity wrt Titan = 6022m/s - Spin = 7.5rpm
14/01/05	09:08:39 UTC	g-switch 1 sets
14/01/05	09:08:46 UTC	Nominal entry detection is enabled
14/01/05	09:08:49 UTC	g-switch 2 sets
14/01/05	09:08:54 UTC	Nominal arming for entry detection is enabled
14/01/05	09:09:25 UTC	Back up arming is disabled by nominal mechanism
14/01/05	09:09:33 UTC	g-switch 2 resets : back up arming would have been enabled if not disabled by nominal mechanism
14/01/05	09:10:07 UTC	g-switch 1 resets and starts the back up entry detection counter
14/01/05	09:10:14.2UTC	SW detects entry
14/01/05	09:10:15 UTC	Nominal entry pyros arming is performed
14/01/05	09:10:20.6UTC	SW fires the pilot parachute mortar and starts the descent timeline (T0 event) - altitude above Titan = 155.8km - Velocity wrt Titan = 310m/s - Spin = 7rpm

The entry activities are illustrated in Fig. 3 which identifies the events on the entry deceleration profile measured by the CASU accelerometers and transmitted by the chain B.

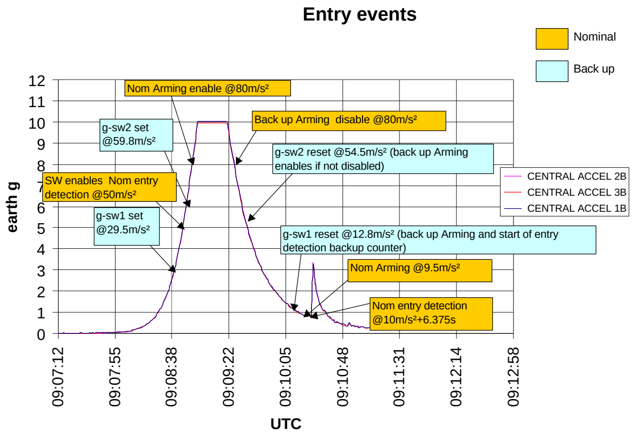

Fig. 3. The Entry Profile and Entry Events

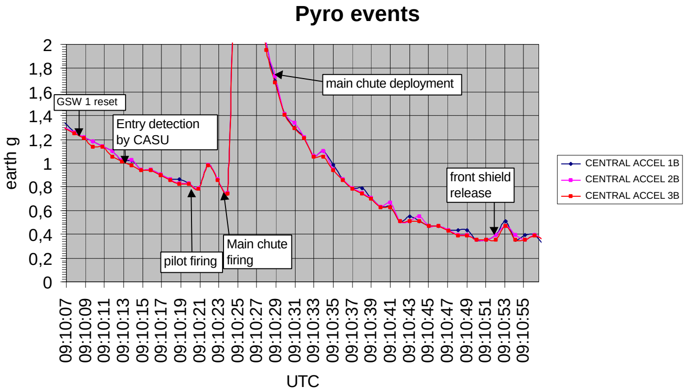

Fig. 4. Entry and early descent Events

All the mechanisms put in place have performed nominally. The start of the descent phase has been initiated by the nominal entry detection mechanism based on the processing of CASU accelerometers, however, they are strong indications that the back up mechanism based on g-switches would have also play its role, initiating the mortar firing and the start of the descent activities 14s later.

A more detailed analysis of the telemetry has shown that the activation of pyro devices during entry and descent was performed by the chain A, which detected “T0” 300ms before the chain B.

Descent and Surface Activities

14/01/05	09:10:23.1 UTC	Back cover is ejected and main parachute is deployed
14/01/05	09:10:51 UTC	ACP instrument is turned ON
14/01/05	09:10:52 UTC	ACP sealing cover and single shot valves opening is enabled
14/01/05	09:10:53 UTC	Front shield is released - altitude above Titan = 150.5km - velocity wrt Titan =115m/s - Spin = 6.5rpm

The occurrence of the entry and post entry activities to set the Probe in descent mode are clearly visible in the CASU acceleration profile, as illustrated in Fig.4. below.

14/01/05	09:11:01 UTC	ACP high dissipation power line is turned ON
14/01/05	09:11:05 UTC	RF High Power Amplifier is turned ON
14/01/05	09:11:07 UTC	Signal Carrier, subcarrier and bit synchroniser are locked at PSA receiver level on board Cassini
14/01/05	09:11:08.8 UTC	HASI instrument booms are energized for deployment
14/01/05	09:11:09 UTC	First Huygens transfer frame from chain B is acquired on board Cassini
14/01/05	09:11:10 UTC	SSP instrument is turned ON
14/01/05	09:11:11 UTC	GCMS instrument inlet is fired
14/01/05	09:11:19 UTC	GCMS instrument outlet is fired
14/01/05	09:11:27 UTC	Protecting cover of DISR instrument is ejected
14/01/05	09:11:41 UTC	DISR instrument is turned ON
14/01/05	09:21:19 UTC	Probe spin is 0rpm - altitude above Titan = 122.6km - velocity wrt Titan = 39.5m/s
14/01/05	09:25:21 UTC	Drogue parachute is deployed and replaces the main chute - altitude above Titan = 114km - velocity wrt Titan = 34m/s - Spin = -2.7rpm

The smaller drogue (also called “stabilizer”) has replaced the main parachute to ensure a timely descent time in the thick Titan atmosphere. The effect of the deployment visible in CASU acceleration profile during descent is shown in Fig.5. The higher Probe instability under drogue can also be noticed.

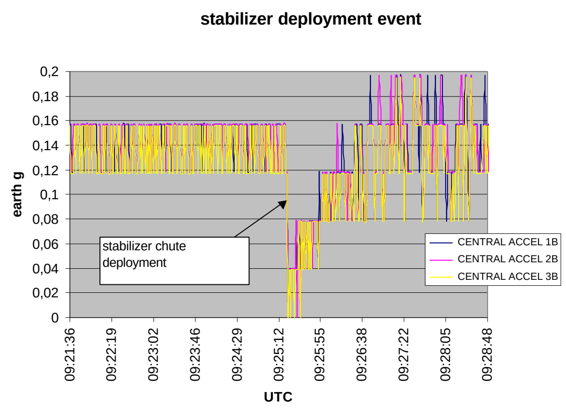

Fig. 5. Stabilizer chute deployment evidence

14/01/05	09:39:11 UTC	GCMS instrument heater line is turned ON
14/01/05	09:42:15 UTC	RAU A and RAU B (altimeters) are turned ON - altitude above Titan = 63.8km - velocity wrt Titan = 27m/s - Spin = -4.7rpm

The Probe Spin, calculated and distributed to the instruments in real time during the Probe descent has been a posteri reconstructed using additional data sets (DISR instrument data, PSA receiver AGC telemetry). It is displayed in Fig.6 which evidences a reversal of the initial spin direction imposed by the Probe-Orbiter separation mechanisms, starting at 09:21:19. Although the amplitude of the spin remained in a range consistent with DISR instrument need for panorama images acquisition, this behaviour was not expected and is not yet explained.

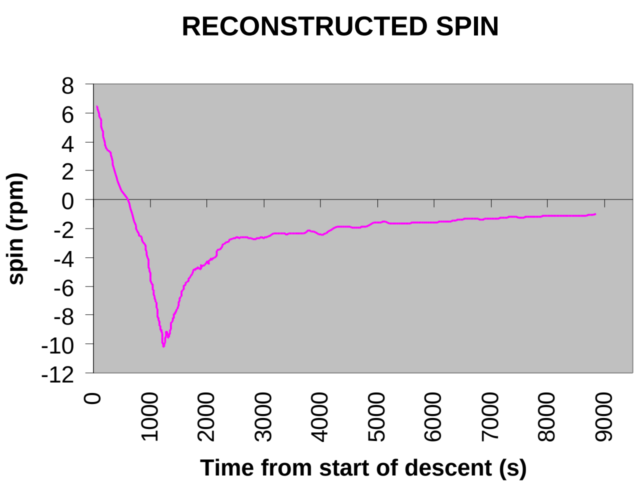

Fig. 6. Reconstructed Spin Profile

14/01/05	10:12:01 UTC	RAU A & B lock is stable but altitude is incorrect - altitude above Titan = 35.17km - velocity wrt Titan = 10.1m/s - Spin = -1.25rpm
14/01/05	10:47:32 UTC	RAU A & B lock at a valid altitude : - altitude above Titan = 17.7km - velocity wrt Titan = 7.38m/s

The altitude calculated from a quite complex algorithm mixing a tabulated theoretical descent profile, RAU A and RAU B and broadcast to the instruments in real time during the Probe descent, has been a posteri reconstructed using additional data sets (mainly HASI pressure and temperature sensors, SSP impact time and GCMS mole fraction). The reconstructed and broadcast altitudes are displayed in Fig.7. It evidences two points :

- the descent time has been some 10mn longer than nominal (147mn instead of 137mn), represented by the theoretical profile, but still inside the expected descent corridor. This has allowed proper triggering of the instruments surface activities,
- both altimeters have locked to anomalous altitudes above about 17km. This translated into a dip in the broadcast data, which became fully consistent again from 10:49, and remained as such until surface impact. This was due to a design feature which could not be flagged during the development of the RAU's, and which was discovered very late in December 2004 in the frame of a balloon flight using the flight spare altimeters. Because a correct lock was finally achieved above 16km, this behaviour has had no significant detrimental effect on the operations.

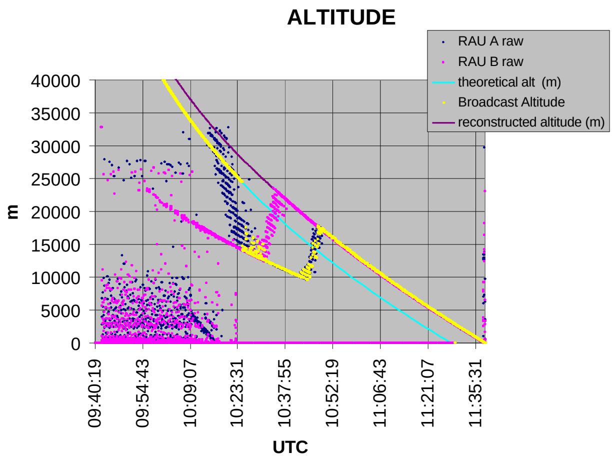

Fig. 7. Altitude Profiles

14/01/05	11:00:21 UTC	ACP instrument is turned OFF
14/01/05	11:23:41 UTC	DISR Surface Lamp is turned ON - altitude above Titan = 1.191km - velocity wrt Titan = 5.5m/s - Spin = -1.15rpm
14/01/05	11:38:11 UTC	Surface impact (detected by CASU, RASU, SSP and HASI sensors) - impact velocity = 4.9m/s
14/01/05	12:24:28 UTC	Start of spurious unlock of bit synchronizer at PSA receiver
14/01/05	12:47:28 UTC	Last TM transfer frame from chain B is received
14/01/05	13:37:32 UTC	PSA Receivers A & B on board Cassini are turned OFF
14/01/05	15:10:00 UTC	Probe is OFF (estimated time of full batteries depletion)

The Probe could transmit telemetry data during some 70mn after landing. The link was interrupted because Cassini finally disappeared beyond Titan horizon, however they clear indications that the Probe remained ON and operational for an additional 140mn.

3. SOME CONCLUSIONS

Huygens has also been a great engineering success. All the units and subsystems have performed nominally, after for some of them having spent more than seven years in OFF state. The Probe wake up and the entry detection processes have been performed by the nominal mechanisms; the two redundant chains A and B have run their pre entry, entry and descent timelines without anomaly. And last but not least, the survival to the impact has not only changed the Huygens descent Probe into a lander, but has also given the opportunity to collect and analyse samples from the surface and images of moon 1.5 billions km from the Sun.

This success has demonstrated the very good adequacy of Galileo / Huygens architectures for entry and descent Probes. The robustness option which has driven these hot redundant, parallel, architectures has permitted to fulfil missions with hard real time constraints with relatively modest processing capabilities (even in the case of Huygens compared to today's figures). It has also saved Huygens from a dramatic scenario in which the Probe mission would have been perfect, while no data could have been acquired by the receivers on board the Orbiter.

Huygens has even been further in the concept of robustness by implementing systematic backups to critical functions and by removing any single failure point common to the two redundant chains,

It is the authors conviction that Galileo Probe/Huygens architectures shall be a priori considered as standard for Entry, Descent and possibly Landing Probe designs.

Another important feature for long duration missions to unknown worlds, is the embedded flexibility. Even though the smallest details of the mission were defined and programmed at Launch – still the robustness concern – Huygens had the capability to have large portions of its software updated, eg. after the refinement of mission parameters based on new observations, or to correct anomalies discovered after launch. This reprogramming capability proved to be essential after an anomaly was found in 2000 in the RF receiver bit synchroniser. As a consequence, the mission geometry was changed, significantly impacting Cassini planning, and Huygens timeline was changed, imposing software patches. The successful mission lived on the 14th of January 2005 is also the result of these modifications.

4. COULD IT HAVE BEEN BETTER ?

The question does not address the fact that, for instance, the mistake having led to not receiving any data from the chain A could have been avoided. The answer is obvious, although the consequences both from science and engineering point of view have in the end been relatively minor.

The point is rather here, to the light of "all what has worked", to critically review some areas where some simplifications or some relaxation of constraints could have led to a better optimisation of the mission. Because a choice had to be made, the mission optimisation will be addressed in terms of scientific return.

A first comment which one can make considering the Huygens Probe mission as a whole is obviously that its duration was significantly longer than foreseen. The first reason is that the Probe survived the impact, and the second is that the available energy was much higher than predicted. Could that higher energy have been anticipated, and possibly used to optimise the mission return ? This is the first reverse engineering attempt we propose to do.

Two separate issues have to be considered in that frame, related to the battery type and related to the energy margin/failure cases policy on the programme. The Huygens batteries, as presented in chapter 1.2, were identical to Galileo Probe ones (identical type, manufacturer, module design). A large number of tests had been carried on Galileo when Huygens was designed [2]. A number of discharge tests were subsequently run on Huygens well before launch. Two flight spare batteries were even fully discharged after nine years of storage before Cassini arrival at Saturn, and exhibited fully nominal capacity. All those data set have finally always proved very consistent and good performance of the batteries. These batteries were also protected against single failures. However Huygens was sized for the case of one full battery loss at separation. On another hand, a very conservative energy budget policy was applied along the programme, considering improbable simultaneous failure cases; this policy was never relaxed.

All this indicates that Huygens, still keeping controlled margins, could have been designed with much less stringent energy constraints. As an exercise, by allocating 800Wh more during 177mn, ie. 270W, the Probe would still have survived 30mn on the surface, sufficiently long to permit an optimum science return. By giving this excess in power exclusively to the redundant RF power amplifiers, it would have, at a first order, allowed to increase the uplink data rate by a factor of 2.6.

Taking another perspective, by installing four batteries instead of five, it would have been possible to allocate 5.3kg additional mass and 90W/4.4h for payload, while still surviving 2h on the surface.

Another comment which can be made is related to the implementation of the back up mechanism. Since all functions have worked using the nominal branch, one could easily deduce that the back up solutions after all, could have been suppressed. It is however the authors conviction that it is not a valid optimisation area. It is indeed still believed to be a safe approach to cover highly critical areas by nominal and backup mechanisms, reinforcing the "golden rule" of Single Failure Tolerance. In addition the impact of the implementation of the Mission Timer Unit and Entry detection backups was minimum in terms of mass (less than 1.5kg in total), complexity and cost. The trade off mission interest vs gain if it was suppressed is definitely in favour of the first point.

As a conclusion of this short search for potential improvements, it must be underlined that the design choices are after the Huygens mission has been performed and the engineering data have been analysed, still fully endorsed. It is on the contrary recognised that a less conservative approach of the energy margins would have offered good opportunities to optimise the overall scientific return.

5. REFERENCES

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